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The potential of solar powered transportation and the case for solar powered railway in Pakistan

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ABSTRACT

The growth of a country can be gaged directly from its growing demand for energy. If the demand for energy is not met in-time then it would severely hamper growth leading to economic meltdown and collapse. Pakistan is a developing economy with a vast potential for industrialization. However, the ever increasing energy deficit faced by the country has led to a severe economic slowdown. Apart from the industrial demand for electricity, transport sector is also a major consumer of energy in the country. This research, keeping in view the importance of transport sector as well as its energy requirements, proposes to utilize solar energy for the development of a solar powered railway transport system in the country. For this purpose, the solar energy potential of Pakistan has been evaluated and a case study for solar powered vehicles is presented, with an aim of utilizing renewable energy resources within the country.

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1. Introduction

Pakistan is located between 23–27° north latitude and 61–76° east longitude on the world map with a total administrative area of 803,950 square kilometers and population of over 160 Million [1]. The country is heavily dependent on imported petroleum for its energy needs [2]. Oil accounted for around 30% of the commercial energy available in Pakistan in 2005 (Fig. 1).Of the total energy consumed in Pakistan, the transport sector accounts for 31.4%, 98% of which comes from petroleum oil products (Fig. 2).

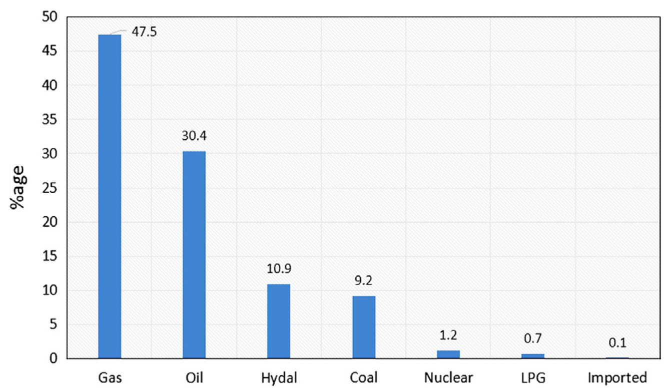


Fig. 1. Primary energy supply by source for 2007–08 (Adapted from [3]).

While natural gas has also been increasingly used to power the transport sector. It is expected that the proven natural gas reserves of the country will exhaust within 24 years [2]. This scenario warrants a serious research towards the development of sustainable energy resources for the country. Already Pakistan is facing a major energy shortfall resulting in massive electricity blackouts and rising cost of transport [5]. In the current energy scenario, the transport and power sector are interlinked and rely heavily on hydro carbon fuels (petroleum oil and natural gas). Therefore, mitigation in one sector will directly complement the other by freeing up resources in one sector to aid the other. This work focuses on research into the prospect of utilizing solar energy for the transport sector in Pakistan. For this purpose, it aims to build upon a previous research to propose a railway based solar transport system that can effectively contribute towards improving the energy shortfall of Pakistan [6].

2. The energy scenario in Pakistan

The per capita energy consumption of a country is a direct indicator for its development. The per capita energy consumption in Pakistan stands at 0.38 t of oil equivalent (TOE) as against a world average of 1.64 TOE with 45% of the population having no access to electricity in Pakistan [7], while those having access to electricity experience massive power shutdowns. There is a serious energy shortfall since Pakistan relies heavily on imported

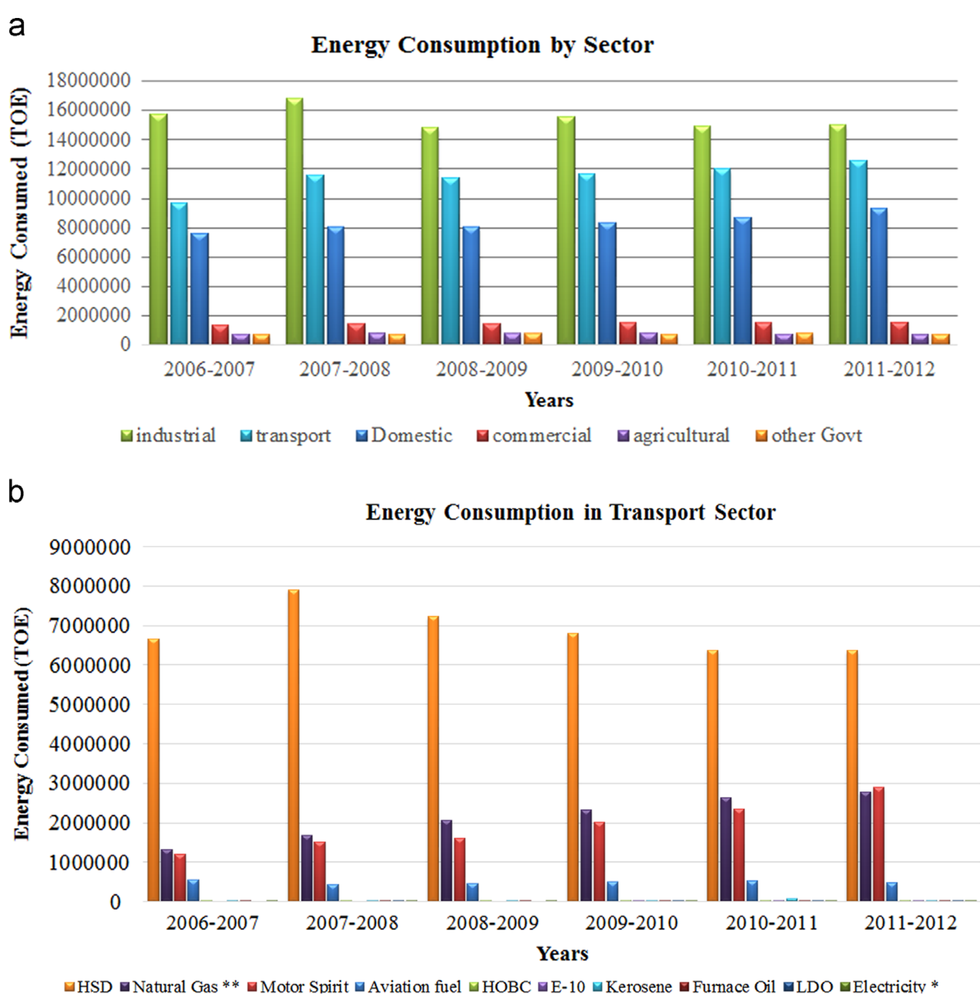
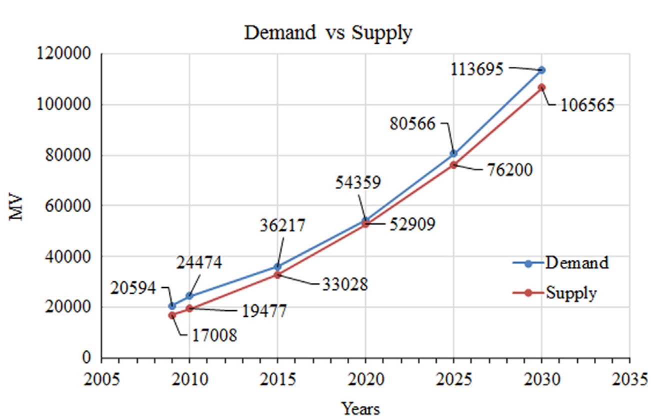


Fig. 2. Sector-wise energy demand mix 2005 [4].

fuel to meet its energy requirements. As mentioned before, most of these imports are in the form of petroleum oils. Pakistan's petroleum oil import bill stood at US$ 15.247 billion in fiscal year 2011–2012 [8]. This figure is likely to experience an upward trend going by the previous trend, where it stood at US$ 12.085 in fiscal year 2010–2011.Going by the current trends, this would reach to about US$ 41 billion by 2022 [9]. In future, petroleum oil prices are expected to rise further, putting greater strain on Pakistan's economy. In order to progress, more energy per capita must be made available in the country. The dependence of Pakistan on this imported fuel is affecting the economy and it is imperative that the country should utilize its renewable resources. Giving the huge potential for alternative and renewable energy, it was proposed that these sources should form at least 12% of the total energy mix by 2022. This will also help mitigate some of the environmental concerns with the use of fossil fuels in line with the global concerns. Even at the global level, there is concern over the depletion of world oil reserves, with the peak oil production estimates ranging from the year 2004–2012, with maximum focus around 2010 [10].

2.1. Power sector

The electricity shortfall in Pakistan is evident from the fact that all parts of the country are experiencing massive electricity blackouts. The electricity shortfall in the country was reported to have reached 7000 MW with the demand at 17,896 MW against a generation of 10,421 MW in 2012 [11,12]. While generation capacity does exist, the high cost along with lengthy time line for completion of hydal power generation projects remain major hurdles in attaining energy self-sufficiency. Power generation thus mainly relies on thermal generation which again requires expensive fuel imports. The trend showing electricity shortfall and future predictions is shown in Fig. 3. It compares the projected peak demand of electricity in the country, by Pakistan Electric Power Company (PEPCO) which is the main power regulating body in Pakistan, with the supply forecast. Bulk of the electricity is produced from fossil fuels; however, hydro contributes around 30% to the total electricity production as the total installed capacity lies around 6400 MW. A 50 MW of wind power has also been recently added to the system. However, the projected demand-supply deficit in 2030 may have severe implications to the overall economy of the country. Overall the electricity generation comprised 66% thermal (using fossil fuels), 30% hydal and 3% nuclear energy (Fig. 4).



Projected demand includes captive power also, Avg growth rate is expected to be about 8%

Fig. 3. Pakistan demand projections (whole country) [13].

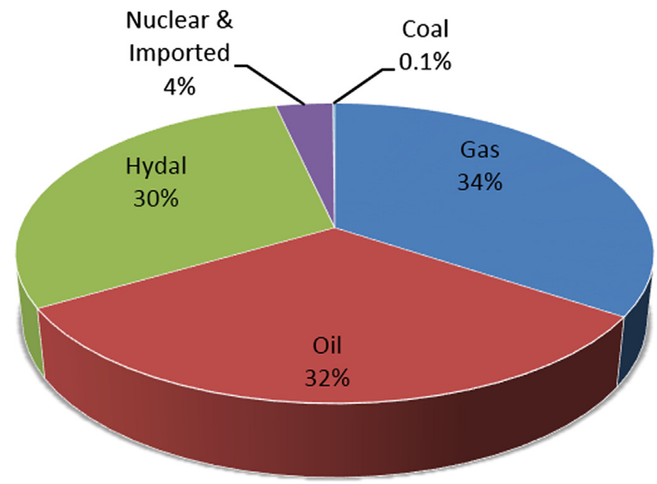


Fig. 4. Energy Generation in Pakistan by source 2007–2008. (Adapted from Ref. [3]).

2.2. Transport sector

According to statistics published by the Energy Conservation Center, Ministry of Water and power, Pakistan, the transport sector accounts for 28% of Pakistan's total energy consumptions. Like electricity, this sector also relies heavily on fossil fuels, mainly petroleum oils (gasoline and diesel). Pakistan currently produces nearly 9.5 billion cubic feet natural gas per annum [14]. Bulk is consumed for power generation 29%, followed by industrial sector 26%, 17% by fertilizer sector and 8% transport sector. During the past decade, focus was laid on switching the transport sector from imported oil to locally produced natural gas in the form of compressed natural gas (CNG). However, the gas reserves in the country are limited and are expected to deplete within 20–61 years, with gas outages and low pressure getting serious by the month [3,15].

The energy shortfall was cited to have cost the country around 4% of its GDP over the past few years [16]. Due to excessive demand from the transport sector, gas supplies were diverted from power generation and the industry leading to shortfalls in these sectors and reduced growth. In total, 47.5% of Pakistan's energy comes from natural gas and 30.5% from oil while 34.3% electricity is generated from natural gas and 32.1% from oil [3]. From Figs. 1 and 4 it is quite clear that transport and electricity generation are linked together in utilizing fossil fuels in the form of oil and natural gas. Therefore any natural gas spared from the transport sector can be utilized either in electricity generation and directly used by industrial sector, thereby reducing power outages, increasing annual growth and strengthening of the economy.

3. Fossil fuels and the environmental concern

It is estimated that from 1751 to mid-2000, around 337 billion tons of carbon has been pumped into the atmosphere by burning fossil fuel, with half of these emissions taking place since the mid 1970's [17]. The transport sector accounted for around 13%of the total CO_2 emissions in 2004 [6,18]. Increasing CO_2 levels increases global atmospheric temperatures, which is widely predicted by environmental scientists to occur more frequently as seen in 2013. Climatic catastrophes are widely attributed to global warming due to greenhouse emissions. Furthermore, the rising temperature can also destabilize the biological balance causing extinction of certain species and a bloom of potentially harmful pathogens that thrive in warmer environments. This could lead to outbreaks of

previously un-known diseases in human populations. Besides CO_2, other fossil fuel emissions including NOx and SOx cause genetic mutations and diseases like lung cancer and skin diseases. In addition, these emissions also cause depletion of ozone layer which leads to greater exposure to harmful solar radiations ultimately causing skin cancer. Overall, all these resulting factors reduce quality of life as well as increasing burden on the limited resources of the health sector of the country.

4. Renewable energy for transport sector

Since fossil fuels are fast depleting, besides being detrimental to the environment, there is a need to shift to renewable sources of energy. Solar energy is the ultimate source of all forms of fossil fuels available on earth, from petroleum oils, natural gas to coal. Solar energy can be used for both electricity generation for the national grid through grid-tied photovoltaic (PV) topologies as well as in transport sector. The transport sector in Pakistan is plagued by inefficiency, traffic jams as well as environmental concerns. The efficiency of all heat engines used in modern automobiles is typically lower as compared with electric power generation. This is due to the fact that these engines do not operate on fixed parameters that can be optimized and incorporated in the mechanical design. As a result, atmospheric pollutants are also released in higher quantities and at street level where public is directly exposed to them [19–21].Thus targeting the transport sector will be beneficial from economic as well as environmental perspective even if fuel saved from transport is used for generating electricity.

4.1. Solar powered transportation

At global level, the transport sector accounted for 27% of the total world delivery energy in 2008 [22] and produced 13.4% of the total greenhouse emissions [23,6]. As already mentioned in the preceding sections, the situation is more critical in the case of Pakistan where 48% of the total petroleum oil consumption was in the transport sector [24].

The interest into solar energy for electric vehicles dates back to late 1970's driven by the global energy crisis as well as environmental issues [25]. From the environmental perspective, solar vehicles provide the best available option with the existing technology offering direct conversion of light to electricity, with zero emissions at operational level. As a result, there are no greenhouse gas emissions with solar panels and the energy payback period is ranging from 1 to 2 years depending on the panel technology used. In this context, thin film technologies generally have energy payback less than a year with traditional C–Si technology having closer to two years [26], with overall panel life of 25 years. Therefore, the usefulness of this technology is immense since it tackles two of the world's major problems in energy and environment, collectively. This is a unique property in itself and makes it vital for our future growth. The alternatives like hydrogen based vehicles must rely on an energy source to produce hydrogen like electrolysis, thus the source of that energy comes into question [6]. Fossil fuels, on the other hand, are all non-renewable and detrimental to the environment.

4.2. Solar powered electric two wheelers: a case study

As a case study, tests were performed to evaluate the performance of electric bikes developed for this study at School of Mechanical and Manufacturing Engineering (SMME), National University of Sciences and Technology (NUST) Pakistan. The prospects for solar charging were evaluated against the standard charging methods i.e. charging from the national grid. Tests were carried out under different operating conditions to fully understand the suitability of such transport in Pakistan. The tests were conducted on two prototypes designated EB 1 and EB 2. Specifications of electric bikes are detailed in Table 1.

The batteries of elecric bike charged by conventional plug-in sockets took six hours to fully charged. Charger voltage and current, battery voltage and current andambient temperature were also logged while charging. In case of solar charging, all experiemnts were performed from 10:00–11:00 AM to 4:00–5:00 PM with ambient temperature between 20 and 22 °C and charger current at 1.5 A. The irradiance at this time was in excess of 600 W/m^{-2}. This inherent system protected the batteries from getting over charged to maintain optimum performance throughout the charging/discharging routines.

4.2.1. City drive cycle test

This test determines the mileage of the electric bike under realistic conditions in one charge, i.e. at 100% state of charge. This test was performed on a track with variable slopes, straight paths, speed breakers and road bumps. The electric bike was driven at a constant speed of 30 km/h. The average of three city drive cycle tests was taken as the official mileage range of the electric bike.

According to Fig. 6, EB-1 attained an average mileage of 41.6 km in one charge and EB-2 achieved average mileage of 29.4 km in one charge as shown in Fig. 4. The reason for difference in mileages of both electric bikes is that EB-1 has lower powered DC motor (500 W) as compared to EB-2 (800 W) however the battery packs for both the electric bikes were the same.

4.2.2. Acceleration-decelaration test

The acceleration test determines the maximum acceleration the electric bike can attain. The acceleration of bikes was calculated by monitoring the time taken by the electric bike to reach maximum speed of 40 km/h shown in Fig. 7.

Table 1
Specifications of electric bikes used for solar charging and performance tests.

Electric bike (EB)	Motor rating (W)	Batteries types	Batteries qty	Equivalent gasoline engine bike
EB-1	500	12 V/20 Ah and 12 V/12 Ah	08 (04 each type)	70cc
EB-2	800	12 V/20 Ah and 12 V/12 Ah	08 (04 each type)	100cc

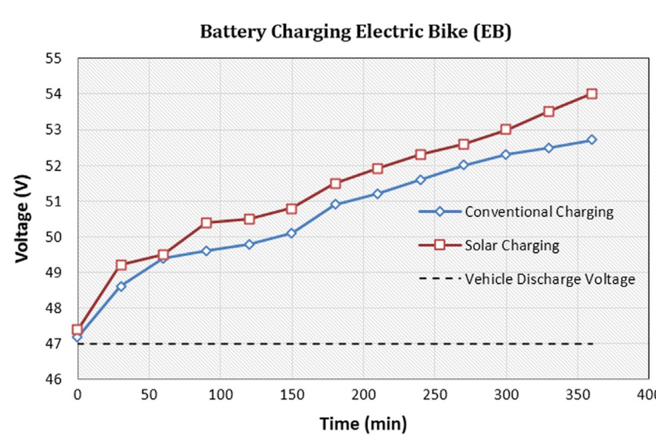


Fig. 5. Conventional and solar charging of batteries used for Electric Bikes (EBs).

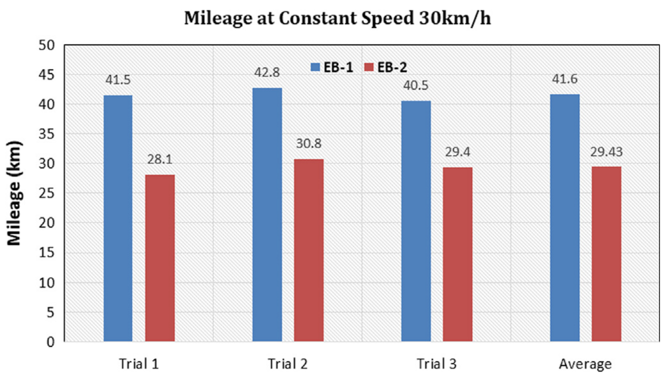


Fig. 6. Mileage comparison of EBs.

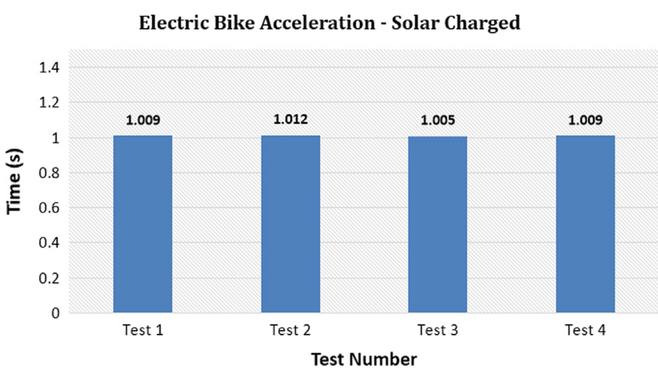


Fig. 7. EBs acceleration tests with solar charged batteries.

Table 2
Price of electricity in Pakistan obtained from different sources [31–33].

S/No	Sources	Cost (Rs)/unit
1	Hydal	0.08
2	Gas	5.21
3	Furnace oil	16.16
4	Diesel	20.8

4.2.3. *Cost comparison*

As shown in Fig. 5, the electric bike got fully charged in 6 h time and consumed 4 KWh of energy in total. In order to compute the total cost of charging the EB through sunlight, Levelized Cost of Electricity (LCOE) through this PV technology was taken into account. The cost of panels, installation and related power electronics have decreased steadily over the past few years with overall system cost as low as 1 $/W for large systems [27,28]. At 1.5 $/W the LCOE turns out to be 9.5 cents/kWh [29]. Other sources put the cost of electricity from off-grid solar power systems at approximately Rs14.40 per kilowatt-hour ($0.15/kWh) [30]. By contrast, grid electricity for most upper-middle class consumers in Pakistan currently costs in the range of Rs11 to Rs13/kWh while diesel-fired generators can cost as much as Rs32/kWh. This translates to about Pak Rs. 38 (approximately US$ 0.4) for a full charge which on average gives about 41.6 km (in one full charge). Consequently, the energy cost per km of Electric bike equates to Rs. 0.91/km. While the cost of electricity from the national grid may appear economical as compared with solar energy, the national grid is suffering from huge power outages. An additional load for transport would increase the price of electricity. This cost also does not include the efficiency associated with AC to DC conversion Table 2.

With solar charging, the electric bike got charged in 6 hours and the average mileage was 39 km in one charge. The running cost of charging the electric bike via solar charger is free (not taking into account the initial installation cost) and hence there is zero cost per km of the electric bike.

4.3. *Limitations of solar powered two-wheelers*

While the case study based on electric bikes does present promising results, it also points to certain limitations that are likely to hinder their practical implementation. Firstly, as in the case for all other personalized transport modes, the electric bikes are not restricted to a predetermined route. As a result, they can only be charged at specified charging stations when parked. During this charging period (about 6 h as shown in Fig. 5), the transport will remain idle. Secondly, the two-wheeler does not offer a reasonable surface area needed to mount a solar panel for onboard charging during operation. Furthermore, the rolling resistance of pneumatic tires also reduces the efficiency. There is therefore, need to implement a solar powered transport system that can effectively address the aforementioned concerns.

4.4. *The case for a solar powered railway system*

For available solar powered transport to be introduced, the performance and range of the vehicle must be maximized. This can be done effectively by maximizing the efficiency of electrical components and reducing the vehicle frontal area for minimum air drag. Furthermore, railway vehicle also offers the benefit of lower rolling resistance as compared with road transport [34]. Also, since railway routes are fixed, pre-planned journey parameters can be implemented efficiently utilizing regenerative breaking as well as off board energy input. When comparing railway transport with road based transport, railway offers higher efficiency (Table 3) as well as environmental benefits (Table 4).

It is clear from Table 3 that public transport is less utilized against full capacity as compared with personal transport. With better marketing and improved service level, public transport has greater prospect of improvement as compared with personal transport. Moreover, with effective design and manufacturing techniques, the weight of light railway vehicles can be reduced considerably, thereby increasing the overall energy efficiency. As shown in Table 5, previous research reported improvement in vehicle weight per passenger from around 200 kg/passenger to 110 kg/passenger [35].

Table 3
Energy consumption of common modes of transport [6].

Mode of transport	Energy consumption (BTU/passenger mile)
Motorcycles	2460 (1.16 passengers)
Cars	3538 (1.55 passengers)
Buses	4242 (9.23 passengers)
Railway (intercity)	2435 (20.91 passengers)
Railway (transit)	2516 (24.51 passengers)
Railway (commuter)	2812 (32.69 passengers)
Railway (average)	2594 (25.80 passengers)
Airplanes	2826 (99.34 passengers)

Table 4
Average CO2 emission for common modes of transport [6].

Mode of transport	CO_2 emissions (g/passenger km)
Cars	110–170
Buses	30–40
Trains	2–5
Airplanes	150–170

In addition to efficiency and energy considerations when compared with road transport, railway transport is less prone to scratch and dents that would require a heavy maintenance cost for PV panels in the case of buses and cars.

5. A solar powered urban railway system

While urban rail based transit system is not a new concept, the implementation of solar power on such a system is indeed on considerable research interest [6]. For this purpose, the infrastructure that must be developed in compatibility with the system requirements. Therefore, an existing underground railways system may not be feasible for the implementation of PV powered drives. It was proposed earlier that an effective transit system utilizing solar energy should be well exposed to solar insolation and must therefore be well raised to avoid shadowing by adjacent structure and buildings. In case of Pakistan where there are not too many tall buildings (due to building regulations within the city) and in ideal location/ position (geographically) to get best solar energy share, use of solar powered urban railway system can become a reality.

5.1. Solar powered urban railway system – the Pakistan perspective

In the context of Pakistan, current urban transport system relies heavily on road based vehicles. This system suffers several inherent problems including traffic congestion and insufficient infrastructure maintenance [37]. In order to mitigate these issues, a rapid bus transit was successfully implemented in Lahore, Pakistan in 2013 [38]. The system comprises buses running on dedicated pathways, parts of which are raised well above the ground level. A similar undertaking was proposed to be undertaken utilizing PV powered railway vehicles [6], which can be implemented in other major cities of the country that suffers from traffic congestion and lack of an efficient urban transit system like the capital city Islamabad and commercial capital Karachi. It may be mentioned here that Pakistan receives an average annual insolation between 200 and 250 W/m² [39] against a global average of 184 W/m² [40]. With specially designed tracks for solar trains, optimized carriage design for larger surface area and reduced drag, fixed charging units at the stations, dedicated roads/ tracks to optimize paths for regenerative breaking and low energy utilization, the implementation of solar powdered railway system is not far from reality.

Table 5
Comparison of vehicle weight per passenger. (Data from Refs. [35,36]).

Vehicle type	No. of passengers	Un-laden weight (kg)	Weight per passenger (kg)
Bus			
Single decker (rigid)	53	9000	170
Double decker	84	12,000	143
Articulated	140	18,000	129
Trolley bus (electric)	100	13,000	130
Hino AK1JRKA (Pakistan)	63	14,000	222
Hino AK1J-RKB CNG (Pakistan)	46	14,000	304
Train			
Metro car (electric)	150	32,500	216
Suburban (diesel)	120	35,400	296
Light railway vehicle			
Tatra T5C5	100	19,500	195
Manchester metrolink	200	46,000	230
Sheffield supertram	220	54,000	245
City class	200	22,000	110

5.2. Salient features of the proposed system

The transport system envisaged in this research incorporates light weight, DC electric powered railway carriages with top mounted solar panels to provide for trickle charging during operation. Since the transport will run on fixed tracks with pre-designated stops, each station can be equipped with solar charging stations. Off board charging can also be incorporated during operation through the provision of caternary wire the third rail. Regenerative braking based on gravity will be utilized for simplicity as well as weight/cost reduction. Each stop will therefore be in the form of an elevated station where commercial centers can be housed at lower levels (as shown in Fig. 8). The capital generated from the associated economic activity can then be utilized for the maintenance of the infrastructure.

6. Conclusions

Pakistan, like other developing countries, is facing an acute shortage of energy. The situation is more serious in case of Pakistan as the economic growth is adversely affected by this shortage of energy (both in the form of electricity and fuel). Ground transport sector consumption is one of the major load on the energy supply of the country and the potential for solar PV transport is huge which needs to be added to other mass transit systems in the country. The ailing economy of Pakistan can no longer support the ever increasing demand for energy and the transport sector can aid in direct contribution towards the economic growth. Therefore, the proposed solution is a solar powered mass transit system (like railway) to firstly reduce the overall number of vehicles in the country, thereby reducing energy supply and demand situation and secondly improving quality of life through reduced environmental pollution. The fuel saved from transport sector, which is a huge burden on the fragile economy, can be diverted to the power generation units to provide

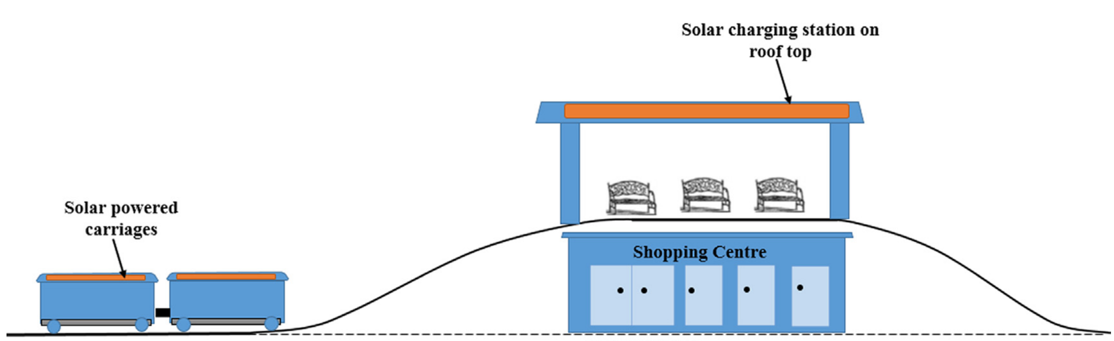


Fig. 8. Schematic of proposed gravitational braking system showing commercialization aspects.

electricity to the local industry to increase the country's GDP, job creation, economic prosperity and social uplift of the people of Pakistan.

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